TECHNOLOGIC PAPERS
OF THE
BUREAU OF STANDARDS

VOLUME 19

Nos. 273-301

F. S. Holbrook

INITIAL TEMPERATURE AND MASS EFFECTS IN QUENCHING

By H. J. French and O. Z. Klopsch

ABSTRACT

In this report are given results of quenching experiments with high-carbon steels in which the speed of cooling was determined at the center of spheres, rounds, and plates of various dimensions quenched from various temperatures into different coolants, such as water, 5 per cent NaOH, oils, and air. The cooling velocity at 720° C. is taken as the best measure of hardening produced, and relations are developed between this and the size and shape of steel quenched. Knowing the described cooling rate at the center of any one size of the simple shapes quenched in any of the customary quenching media, such as oils and aqueous solutions, the velocity in any other size in such shapes can be closely approximated from the included data when the steel is quenched from any temperature between 720 and 1,050° C. Typical examples are given.

CONTENTS

I. INTRODUCTION

During the past 20 or 30 years a great deal of attention has been given to the properties produced in carbon and special steels by quenching and tempering and to the constitutional changes brought about by different heat treatments. Helpful diagrams have been prepared which not only promote a better understanding of the changes taking place, but also permit surprisingly accurate predictions of the properties which will result from different heat treatments.

It is, for example, now generally well known that the properties of a given steel depend, primarily, upon the temperature from which it is cooled and the manner of cooling, and that this latter variable is dependent upon the coolant which is used and the size and shape of the steel under treatment. While the effects of varying mass upon the resulting properties have been studied, little attention has been given to the changes in cooling rates except in a very general way. More nearly quantitative information in this respect would be helpful in the selection of correct heat treatments as well as in comparisons of quenching media, and with this in view the experiments described in this report were carried out.

For results which would be most generally useful a study should be made of the temperature distribution as well as the cooling at the center of different sizes and shapes of steel. The described experiments are, however, restricted to the latter phase and will form a basis of comparison for additional work which it is hoped will be undertaken at a later date.

II. PREVIOUS INVESTIGATIONS

It is possible to gain a general idea of the effects of size and shape on the cooling of steels from the theory of heat conduction first perfected and applied by Fourier,[1] but while some results are obtained which appear consistent with actual experience or tests they can not be considered quantitative they necessitate elaborate and tedious calculations and require various assumptions which introduce an element of doubt upon the validity of many of the conclusions which are drawn.

Comparisons by Heindlhofer [2] of a mathematical study of the temperature changes in a hot body after quenching and experimental cooling curves of metal cylinders quenched in water developed a number of discrepencies with the several theories on rapid cooling. The principal feature of interest in connection with the experiments

[1] Refer to such texts as "An introduction to the mathematical theory of heat conduction," by L. R. Ingersoll and O. J. Zobel, (1913) Ginn & Co., New York, which includes references to original articles.

[2] K. Heindlhofer, "Quenching: A mathematical study of various hypotheses on rapid cooling," Phys. Rev., 20, pp. 221–242; 1922.

to be described is that the cooling time was found to be proportional to the square of the diameter of the cylinder when quenched in the theoretically most rapid coolant in which the surface of the metal is instantaneously cooled to the final temperature.

A theoretical study of the cooling of hot bodies in gases and liquids was more recently reported by Seeliger,[3] who reviewed several available theories and emphasized the fact that they do not permit an exact solution but make possible useful deductions.

Experimental cooling curves of large sections have been obtained by a number of investigators. Fry [4] studied large solid and hollow-bored axles quenched in heavy and light oils, water, air and oil-water compounds, but due to differences in quenching temperature and the introduction of other variables into the several experiments no general conclusions can be drawn. Law [5] investigated the cooling at the center of 18-inch cubes quenched in a water spray, a water bath, an oil and air, and likewise determined the resulting tensile properties from center to surface. The tensile strength gradients were greatest from the water bath quenching, but a maximum difference of only 1,000 lbs./in.^{2} was found at the center in the cubes quenched in the various media (excepting air), thus indicating that the thermal properties of the steel have more to do with the center cooling in such large masses than the coolant used.

Bash [6] reported heating and air-cooling curves taken at different points in a 24-inch ingot, while Knight and Hansen [7] studied the cooling at a point 2 inches from the edge of an 8-inch round, 14-foot long, when quenched in cottonseed oil.

Janitzky [8] devoted considerable attention to the experimental study of mass effects in heat treatment and developed a formula giving the relation between the hardness produced in various sizes and shapes of carbon and alloy steels when tempered at different temperatures subsequent to hardening. He also derived useful relations by which it is possible to approximate the time required to reach any temperature in air-cooling rounds of various dimensions from different temperatures.

---

[3] R. Seeliger, "Die Abkühlung heisser Korper in Gasen und Flüssigkeiten," Physik. Zeitschr., **26**, p. 282; 1925.

[4] L. H. Fry, "Notes on some quenching experiments," Jour. Iron and Steel Inst., **95**, p. 119; 1917.

[5] E. F. Law, "Effect of mass on heat treatment," Jour. Iron and Steel Inst., **97**, p. 333; 1918.

[6] F. E. Bash, "Forging temperature and rate of heating and cooling of large ingots," Transactions, Am. Inst. of Mining Engrs. "Pyrometry" volume, p. 614; 1920.

[7] O. A. Knight and F. F. Hansen, "Heating, quenching, and drawing large steel forgings," Chem. and Met. Eng., **20**, p. 590; 1919.

[8] E. Janitzky, "Hardness formulas," Iron Trade Review, **69**, p. 1079; 1921. "Influence of mass in heat treatment," Chem. and Met. Eng., **25**, p. 783; 1921. "Mass in the heat treatment of steel," Iron Age, **109**, p. 658; **110**, p. 788; 1922. "Influence of size on heat treating," Am. Machinist, **50**, p. 1153; 1919. "A contribution to the problem of the influence of mass in heat treatment," Trans. Am. Soc. for Steel Treating, **2**, p. 55; 1921. "New development on the influence of mass in heat treatment," Trans., A. S. S. T. **2**, p. 377; 1922. "Characteristics of air-cooling curves," Trans., A. S. S. T., **3**, p. 335; 1922.

A feature of particular interest is that the surface per unit of volume, which in plates, rounds, and spheres is in the ratio of 1, 2, 3, when the ends and edges are neglected, is definitely related to the properties produced by quenching.

The effects of size on the tensile properties of quenched or quenched and tempered steels were studied by Zimmerschied[9] and by Straub.[10] While much useful information was obtained by both investigators, their results do not come within the field to be covered in this report and therefore will not be reviewed in detail.

One of the most interesting points in published data was given by McCance,[11] who showed that the cooling velocity at the center of the high-carbon steel cylinders quenched in water by Portevin and Garvin,[11] when taken at a fixed temperature of 700° C., was inversely proportional to some power of the diameter greater than 1 but less than 2.

III. EXPERIMENTAL METHODS USED

The methods of test employed were identical with those described in detail in a previous report.[12] Steel or other metal specimens of the desired form and dimensions were quenched from a definite temperature in known solutions and time-temperature cooling curves taken at the center of the samples with the aid of platinum, platinum-rhodium thermocouples, and a "string galvanometer."

Seven major sets of experiments were first carried out in which four coolants were used representing a wide range in "hardening power," viz, 5 per cent sodium hydroxide in water, water, a commercial quenching oil (referred to as No. 2 oil) and air. Steel specimens were all cooled from 875° C. and held motionless in the coolant which was at ordinary room temperatures (18 to 22° C.). High-carbon steel (0.89 per cent C) rounds varying from ½ to 2 inches in diameter, but with a fixed length-diameter ratio of 4 were quenched in each of the four coolants; a group of ball-race steel spheres (0.98 per cent C, 1.63 per cent Cr), ¾ to 2⅞ inches in diameter, were quenched in water and another in the prepared oil, while high-carbon steel plates (from 0.85 to 1.15 per cent C) ⅜ to 2 inches thick with a ratio of 4 : 4 : 1 in width, length, and thickness were cooled only in water. Subsequently, the effects of quenching temperature were investigated and experiments carried out with a large sphere and irregularly shaped pieces as given in the various sections of this report.

While several methods of comparison are referred to in discussing the effects produced by the different coolants, the primary one is

---

[9] K. W. Zimmerschied, "Influence of mass in heat treatment of steel," Iron Trade Rev., **53**, p. 84; 1913.

[10] T. G. Straub, "Relative size in heat treatment," Iron Age, **104**, p. 167; 1919.

[11] A. McCance, "Discussion of report by A. M. Portevin and M. Garvin: The experimental investigation of the influence of the rate of cooling on the hardeni g of carbon steels," Jour. Iron a id Steel Inst., **99**, p. 563; 1919.

[12] H. J. French and O. Z. Klopsch, "Quenching diagrams for carbon steels in relation to some quenching media for heat treatment," Trans., Am. Soc. for Steel Treating, **6**, p. 251; 1924.

the cooling velocity at 720° C., as it has already been shown[13] that in quenching carbon steels this is the best single measure of "hardening power"[14] which can be secured from a cooling curve. It gave accurate information concerning the hardening produced and warranted retention, at least temporarily, for further experimental work.

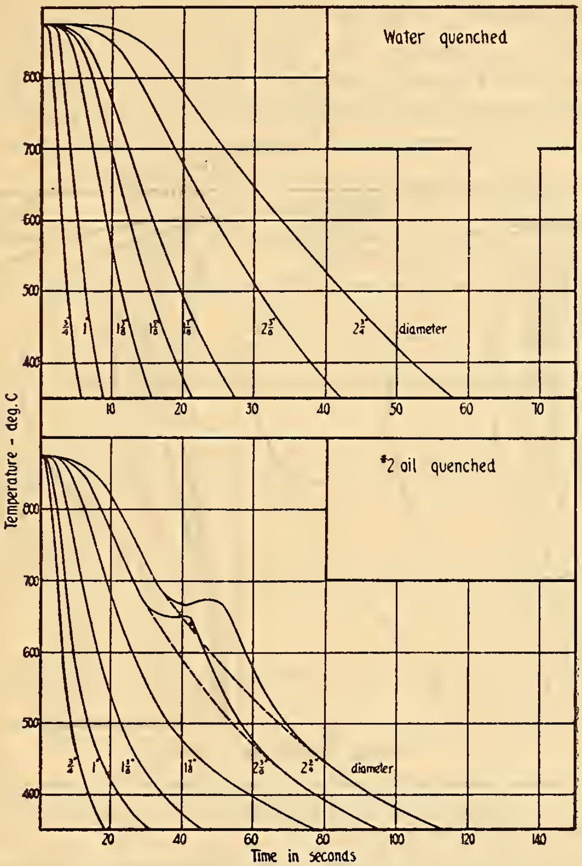


FIG. 1.—*Time-temperature cooling curves at the center of ball race steel spheres of different sizes quenched from 875° C. into either motionless water or No. 2 oil at 20° C.*

IV. EXPERIMENTAL RESULTS

1. TIME-TEMPERATURE COOLING CURVES

To illustrate the type of experimental data on which the various comparisons in this report are based, time-temperature cooling curves are reproduced in Figure 1 for the center of spheres of various sizes

[13] See footnote 12, p. 592.

[14] The term "hardening power" as used in this report refers to effects produced on the thermal transformations, microstructure, and hardness of carbon steels by different media under otherwise comparable conditions of treatment. It is general in nature and considered to be proportional (qualitatively) to the cooling velocity at 720° C. Thus the higher this cooling velocity the higher is the "hardening power."

quenched in water or in oil. These have been replotted directly from photographic records of the time-deflection changes in the "string galvanometer."

There are no striking variations in the character of the cooling curves obtained for the different sizes except for the location and magnitude of the heat effects of transformations. When at low temperatures these are small and do not appreciably change the cooling rates so no attempt has been made to indicate their position and magnitude in Figure 1; they will readily be observed when large, as in the oil-quenched spheres 2⅜ and 2¾ inches in diameter, because the resulting curves are quite different from those which would be

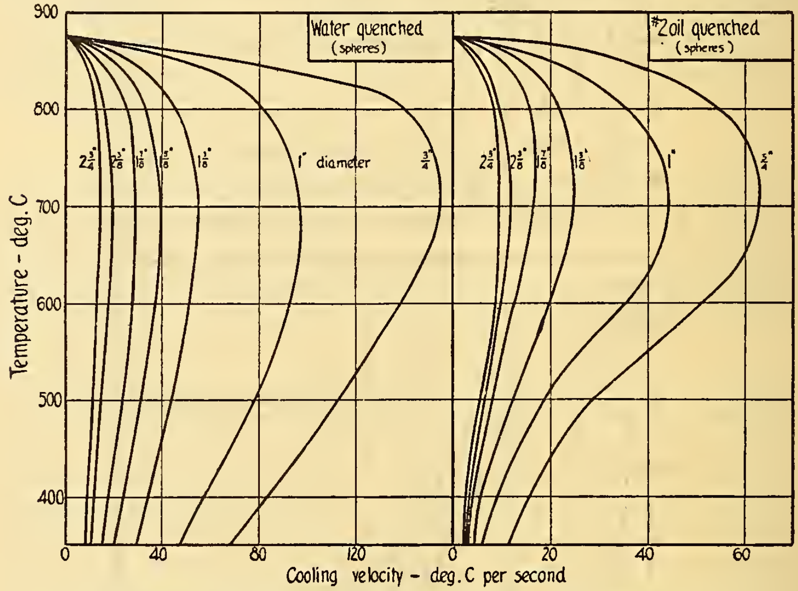


FIG. 2.—*Cooling velocity-temperature curves taken at the center of ball race steel spheres of different sizes quenched from 875° C. into either motionless water or No. 2 oil at 20° C.*

The transformations in the 2⅜ and 2¾ inch diameter spheres quenched in oil have been disregarded in plotting the smooth curves.

obtained on a transformationless metal. This is clearly indicated by the dotted lines in Figure 1. In no case, however, is the selected basis of comparison (the cooling velocity at 720° C.) affected by any of these thermal effects, large or small, as they occur below this temperature.

The similarity in the cooling curves obtained in a given coolant on different sizes is, perhaps, more clearly shown in Figures 2 and 3 by the changes in velocity with temperature. The maximum in a given coolant is found at one temperature for all sizes and the curves are of the same form; they differ only in the numerical values of the cooling rates and the magnitude of the changes in rate with temperature.

It is worthy of note that when quenching from the "standard" temperature of 875° C. into oil or water the chosen basis for comparison (the cooling velocity at 720° C.) is taken at practically the maximum speed of cooling. The changes in rate on either side of this maximum occur slowly, so that the cooling rate selected is being taken from a relatively flat portion of the curves and helps materially in giving exceedingly regular results.

The curves for air cooling in Figure 3 show that the maximum velocity is much closer to the quenching temperature than in the

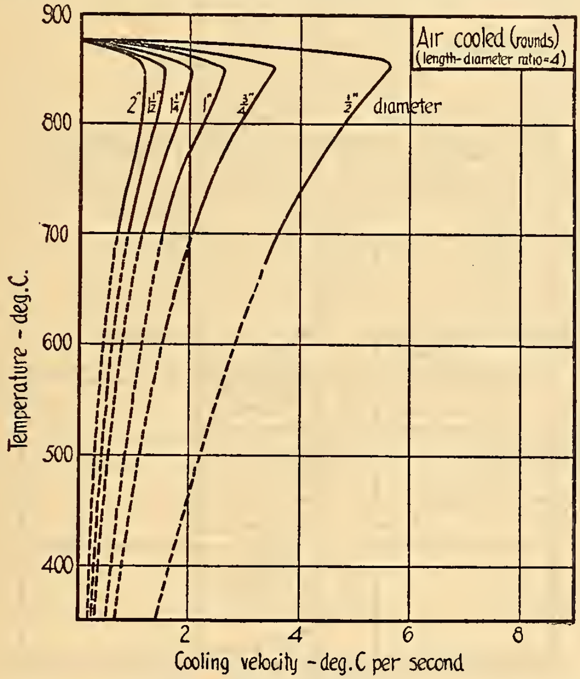


FIG. 3.—*Cooling velocity-temperature curves taken at the center of 0.89 per cent C steel rounds of different sizes cooled from 875° C. into still air at 22° C.*

Dotted lines indicate an extrapolation in which the heat effects of the transformations are neglected

case of either oil or water (fig. 2) in which it occurs at about 0.8 of the initial temperature.

2. EFFECT OF SIZE AND SHAPE ON THE CENTER COOLING VELOCITY, TAKEN AT 720° C.

The effect of diameter in spheres and rounds and thickness in plates upon the center cooling velocity at 720° C. is shown in Figure 4. The relation between the diameter or thickness and this cooling velocity is very closely approximated by the general equation

$$V D^n = c \qquad (1)$$

in which V is the cooling velocity at 720° C. in degrees Centigrade per second, D is the stated dimension in inches (diameter for rounds and spheres and thickness for plates) and "n" and "c" are constants, the values of which are given in Table 1.

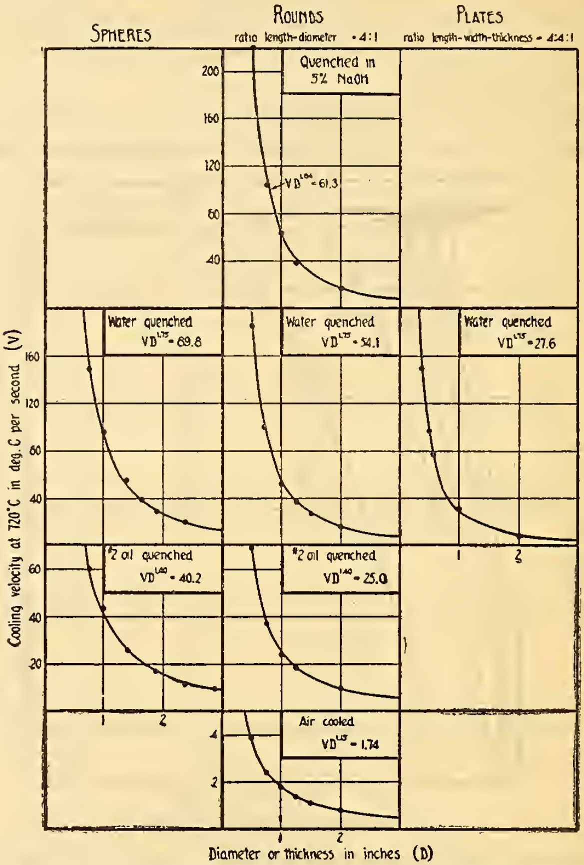


FIG. 4.—*Relation between the center cooling velocity, taken at 720° C. and the diameter or thickness of high carbon steel spheres, rounds, and plates quenched from 875° C. into various coolants*

TABLE 1.—*Numerical values of the constants for equation (1)*

[For ratio of length to diameter in rounds=4. For ratio of length to width to thickness in plates=4:4:1]

Conditions	Value of— "n"	Value of— "c"
Rounds quenched in 5 per cent NaOH from 875° C	1.84	61.3
Spheres quenched in water from 875° C	1.75	89.8
Rounds quenched in water from 875° C	1.75	54.1
Plates quenched in water from 875° C	1.75	27.6
Spheres quenched in No. 2 oil from 875° C	1.40	40.2
Rounds quenched in No. 2 oil from 875° C	1.40	25.0
Rounds cooled in air from 875° C	1.15	1.74

Comparison of these constants shows that the numerical value of the exponent "n" is a function of the coolant while "c" is dependent upon the shape of the material as well, and, hence, upon the surface per unit of volume.

It may now be stated that in quenching:

(a) The cooling velocity, in the neighborhood of 720° C., at the center of spheres, rounds, and plates is inversely proportional to some power of the diameter (or thickness) greater than 1 and less than 2.

(b) This power varies for the different coolants; it is close to 1 for air (1.15), approaches 2 in 5 per cent sodium hydroxide (1.84), and increases generally with the rapidity of the coolant.

At first glance it would appear that the value of the exponent "n" in formula (1) might be used directly or at least indirectly to obtain a number truly expressing the "hardening power" of any coolant, as it is neither dependent upon the size nor the shape of the material. Such a derived value would, of course, be based on the assumption that the cooling velocity at 720° C. was a quantitative measure of the martensitization or hardening produced in any steel which is not exactly true. Under ordinary conditions with carbon steels it is a sufficiently close criterion, so that really large errors would not be introduced on this score, but there is another and more important reason why such a derived numerical value can not be used. This will later be discussed in detail.

Some interesting and useful comparisons can be developed from the data given in Figure 4. The first has to do with the effect of the shape of the steel on the center cooling velocity taken at 720° C. (subsequently called "cooling velocity" or "cooling rate") and may be stated as follows:

TABLE 2.—*Experimental data for the first seven sets of quenching experiments*

0.98 PER CENT C, 1.63 PER CENT CR, STEEL SPHERES QUENCHED FROM 875° C. INTO MOTIONLESS COOLANTS AT 20° C.

Size (in inches)	Surface	Volume	Weight	Ratio surface: Volume	Cooling rate at 720° C. in ° C. per second	
	Inches²	*Inches³*	*Grams*		H_2O	*Oil*
¾	1.767	0.222	25.5	8	[1] 148.5	[1] 60
1	3.142	.523	64	6	95	[1] 43.5
1⅜	5.91	1.326	170.5	4.46	55	[1] 25.2
1⅝	8.08	2.186	286	3.70	39	----------
1⅞	11.05	3.450	438	3.20	28	[1] 16.6
2⅜	17.50	6.790	894.5	2.58	20	[1] 11.4
2.77	24.10	11.110	1,425	2.10	14	9

[1] Average of two values.

TABLE 2.—Continued

0.89 PER CENT CARBON STEEL ROUNDS QUENCHED FROM 875° C. INTO MOTIONLESS COOLANTS AT 20° C.

Size (in inches)	Surface	Volume	Weight	Ratio surface: Volume	Cooling rate at 720° C. in ° C. per second		
	*Inches*²	*Inches*³	*Grams*		H_2O	*No. 2 oil*[2]	*Air*
½ by 2	3.53	0.393	46.5	9	185	69	3.84
¾ by 3	8.05	1.326	167	6	93	37	[1] 2.37
1 by 4	14.14	3.142	396	4.5	[1] 52	23.5	1.77
1¼ by 5	22.09	6.135	780	3.6	[1] 37	18.5	1.36
1½ by 6	31.81	10.602	1,350	3.0	[1] 27.4		1.07
2 by 8	56.53	25.13	3,195	2.25	15.3	9.4	.80

Size (in inches)	Surface	Volume	Weight	Ratio surface: Volume	Cooling rate at 720° C. in ° C. per second
	*Inches*²	*Inches*³	*Grams*		*5 per cent NaOH*
½ by 2	3.53	0.393	46.5	9	222
0.744 by 2.98	7.84	1.295	161.2	6.05	105
0.99 by 3.98	13.92	3.065	383.5	4.54	64
1.24 by 4.96	21.77	5.980	760	3.64	37
1.99 by 7.98	56.12	24.83	3,156	2.26	16.8

HIGH-CARBON STEEL PLATES QUENCHED FROM 875° C. INTO WATER AT 20° C.

Size (in inches)	Surface	Volume	Weight	Ratio surface: Volume	Cooling rate at 720° C. in ° C. per second
	*Inches*²	*Inches*³	*Grams*	*Volume*	H_2O
⅜ by ⅜ by 1½	6.75	0.844	104.1	8	149
½ by 2 by 2	12	2	253	6	97
$\frac{9}{16}$ by $\frac{9}{16}$ by 2¼	15.19	2.85	353	5.33	[1] 77
1 by 4 by 4	48	16	2,026	3	31
2 by 7.89 by 7.92	188.04	125	15,961	1.51	6.9

[1] Average of two values.
[2] No. 2 oil is a prepared commercial quenching oil, the same as referred to in a previous report. Refer to footnote 12, p. 592.

(*c*) For a given size the highest cooling velocity is obtained in spheres, an intermediate rate in rounds, and the lowest in plates.

This is due to the fact that a given size of sphere has a larger amount of surface per unit of volume by which the heat can be taken away than a round of the same diameter, and similarly a round has a larger surface per unit of volume than a plate of equal thickness. A more detailed consideration of the relation of the surface and surface per unit volume to the cooling velocity will be given in subsequent sections of this report.

A more generally useful and quantitative statement covering these relations is that—

(*d*) For equal cooling velocity the ratio of the diameter of spheres to the diameter of rounds and thickness of plates is as 4: 3: 2, provided the length of the cylinder is four times its diameter and the length and width are each four times the thickness of the plate.

Thus, the cooling velocity at 720° C. and the hardening at the center of a 1-inch sphere is the same as in a ¾-inch round, 3 inches long, and a ½-inch thick plate, 2 inches long by 2 inches wide. Confirmation of this for certain sizes can be obtained directly from the experimental data tabulated in Table 2, but more convincing proof can readily be secured mathematically from the general relationship given by formula (1) ($V\ D^n=c$); at the same time such computations will show the degree of accuracy attained in the experiments from which the values of "n" and "c" were determined.

If V_s = center cooling rate, taken at 720° C. for spheres,
V_r = center cooling rate, taken at 720° C. for rounds,
V_f = center cooling rate, taken at 720° C. for plates,
D_s = the diameter of the sphere,
D_r = the diameter of the round,
D_f = the thickness of the plate,

then the relation between size and cooling velocity in water quenching is given by

$$V_s D_s^{1.75}=89.8 \text{ or } V_s=\frac{89.8}{D_s^{1.75}} \text{ for spheres} \tag{2}$$

and

$$V_r D_r^{1.75}=54.1 \text{ or } V_r=\frac{54.1}{D_r^{1.75}} \text{ for rounds} \tag{3}$$

For equal cooling velocity in spheres and rounds V_s equals V_r and $\frac{89.8}{D_s^{1.75}}=\frac{54.1}{D_r^{1.75}}$ or

$$\frac{D_s}{D_r}=\left(\frac{89.8}{54.1}\right)^{\frac{1}{1.75}} \tag{4}$$

Here the right-hand side of equation (4) represents the ratio of diameters in spheres and rounds, which will have the same cooling rate and when reduced is found to be equal to 1.333. Similar computations carried out for spheres and plates quenched in water give a ratio of diameters equal to 1.960; for spheres and rounds quenched in oil it is 1.399.

When these are compared to an assigned value of 4 to spheres the following results are obtained, which are equal, within limits of experimental error, to the stated ratios of 4: 3: 2:

	Ratio of diameters giving the same cooling rate at 720° C. in—	
	Water quench	Oil quench
Spheres	4	4
Rounds	3	2.86
Plates	2.04	----------

3. DATA SHOWING THAT THE COOLING TIME FOR CERTAIN INTERVALS IS INVERSELY PROPORTIONAL TO THE COOLING VELOCITY, TAKEN AT 720° C.

It will probably be well at this point to demonstrate that the cooling velocity selected for previous comparisons is proportional to the cooling time, provided this is taken over an interval which does not begin or end at a temperature within the range of large heat effects of transformations. Not only does this make the foregoing comparisons of more general interest but also demonstrates again that the form of the cooling curves, or, to express this somewhat differently, the manner of cooling at the center of spheres, rounds, and plates, is not altered appreciably by variation in size (within the limits of the experiments).

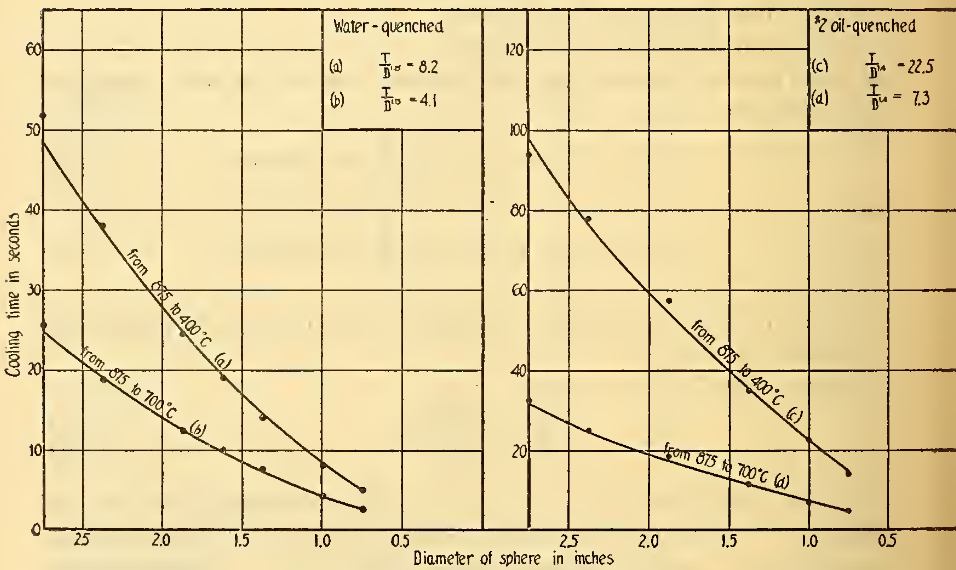


FIG. 5.—*Relation between the center cooling time and the diameter of ball race steel spheres quenched from 875° C. into either motionless water or No. 2 oil at 20° C.*

In order to avoid those temperatures in which thermal effects would change both cooling rates and times and at the same time include in comparisons the cooling at both high and low temperatures, two ranges were selected, (1) the cooling time from the quenching temperature (875° C.) to 700° C., (2) the cooling time from 875 to 400° C.

As shown in Figure 5 for spheres quenched in oil or in water, the relation between cooling time and diameter is closely approximated by a hyperbola having the general equation

$$\frac{T}{D^{n}} = c_1 \qquad (5)$$

in which T is the cooling time in seconds, D is the stated dimension in inches, and "n" and "c_1" are constants.

The numerical value of "n" in this equation (5) is the same as that in equation (1) for a given coolant. Therefore, the cooling time from either 875 to 700° C. or 875 to 400° C. is inversely proportional to the velocity and may be determined if the values of "c" and "c_1" are known for the various shapes quenched in the different coolants. This may be expressed as follows:

$$T=\frac{c\,c_1}{V} \tag{6}$$

in which "c_1" is the constant of equation (5) (cooling time formula) and "c" is the constant of equation (1) (cooling velocity formula).

The numerical values of "c" and "c_1" are, as previously indicated, dependent both upon the coolant and the shape of the material. On this account they are not here included for all shapes and coolants.

It may now be stated that—

(e) Provided the chosen interval does not begin or end at a temperature within large thermal transformations, the cooling time at the center of spheres, rounds, and plates is inversely proportional to the cooling velocity taken at 720° C.

4. EFFECT OF EXPOSED SURFACE IN ROUNDS, SPHERES, AND PLATES ON THE CENTER COOLING VELOCITY, TAKEN AT 720° C.

The foregoing comparisons and formulas have been given for the sake of completeness and as a matter of general interest, not because they are the most generally useful of those which may be secured. Aside from the necessity of having the numerical value of the constants c (equation (1)) and c_1 (equation (5)) for each set of conditions involving change in shape and coolant, the relations do not apply directly to rounds having a length-diameter ratio other than 4, and likewise can only be used for plates in which the length and width are each four times the thickness. It is therefore desirable to seek a more generally applicable relation between the cooling rate and the size and shape of material.

In cooling a heated mass heat must flow from the central zone toward the surfaces and be taken away from the body through the surface of the metal which is in direct contact with the coolant. Under ordinary conditions of heat treatment there is an unlimited supply of the coolant in comparison with the mass of metal to be cooled, so that the time required to take the heat away, and, hence, the rate of extraction, will be a function of the amount of heat to be removed. With a fixed initial (quenching) temperature this is proportional to the volume of a given metal. Since the exposed surface and volume are both of importance in determining the cooling rate in a given coolant, it is reasonable to expect that the most general relation will be found in comparison of the surface per unit volume and the cooling velocity and not in consideration of the amount of surface alone.

While the surface-cooling velocity curves for the different shapes as shown in Figure 6 are of the same general type as those in Figure 4, in which diameter or thickness is plotted against the cooling velocity, it can readily be shown that they apply only to the specific sets of conditions covered by the experiments and are not of more general use. Therefore, no attempt has been made to represent these curves mathematically.

5. RELATION BETWEEN THE SURFACE PER UNIT OF VOLUME AND THE COOLING VELOCITY, TAKEN AT 720° C.

If the cooling velocity, taken at 720° C., is compared to the surface per unit of volume for each of the basic shapes (spheres, rounds, and plates) a family of hyperbolic curves is obtained which are closely approximated by

$$V=\left(\frac{S}{W}\right)^{n}\times C_2 \tag{7}$$

in which V is the cooling velocity in degrees Centigrade per second, taken at 720° C., S is the surface area in square inches, W is the volume in cubic inches and "n" and "C_2" are constants, the values of which are given in Table 3. ("n" is the same as in previous equations.)

TABLE 3.—*Numerical values of the constants for equation (7)*

Conditions	Value of— "n"	Value of— "C_2"
Rounds quenched in 5 per cent NaOH from 875° C	1.84	3.86
Spheres quenched in water from 875° C	1.75	3.89
Rounds quenched in water from 875° C	1.75	3.91
Plates quenched in water from 875° C	1.75	4.03
Average		3.94
Spheres quenched in No. 2 oil from 875° C	1.40	3.22
Rounds quenched in No. 2 oil from 875° C	1.40	3.03
Average		3.12
Rounds cooled in air from 875° C	1.15	.31

Unlike previously developed relations both constants are independent of the shape of the material and under otherwise fixed conditions are determined solely by the coolant. This, however, only applies to the simple and basic shapes covered by the experiments, namely, spheres, rounds, and plates, but is not restricted to a fixed ratio of length to diameter in the rounds or a fixed ratio of length to width to diameter in the plates. Equation (7) is thus more generally applicable than the previous ones. Experimental confirmation of this is given in Figure 7, in which is shown the effect of surface per unit volume on the cooling rate for various coolants. Spheres,

rounds with different ratios of length to diameter, and plates in which the ratio of length to width to diameter has been varied are all plotted to the same coordinates and fall closely on a smooth curve for each coolant. From the data given in Figure 7 it is possible to approximate the cooling velocity for any of the simple basic shapes, or this can be determined from equation (7) and the values of "n" and

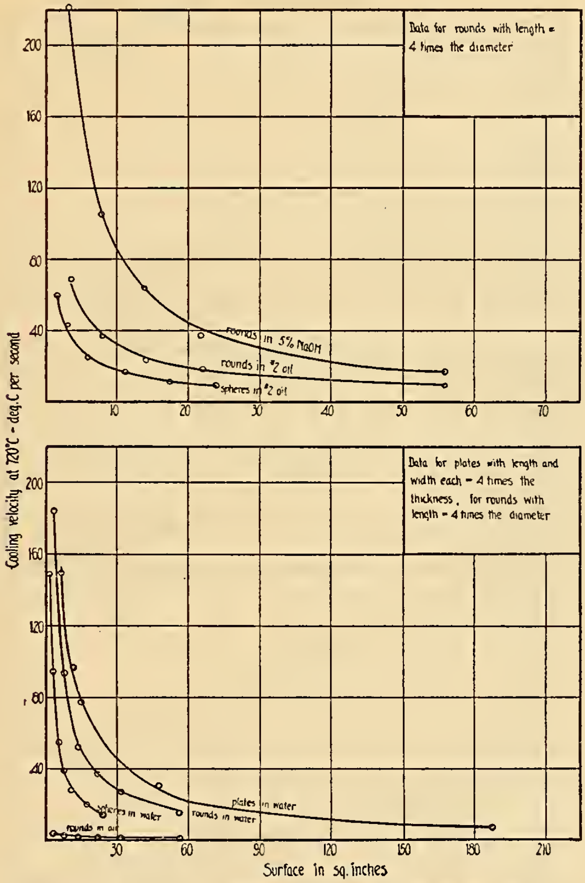


FIG. 6.—*Relation between the center cooling velocity, taken at 720° C. and the exposed surface in quenching various sizes and shapes in different coolants from 875° C.*

"C_2" given above for 5 per cent sodium hydroxide in water, water, a commercial quenching oil, and air cooling. If the critical cooling rates are known for a given steel, or quenching diagrams are available, such as have already been determined for carbon steels by the authors,[15] it follows that the degree of hardening can be predicted or that the size which will harden completely throughout (martensitization) can be determined, whether for a round, sphere, plate, or cube.

[15] See footnote 12, p. 592.

Inasmuch as "n" and "C_2" of equation (7) are independent of the shape of the material, the center cooling velocities of spheres, rounds, and plates will be equal when their respective surfaces per unit of volume are equal. The sizes which have equal surfaces per unit of volume in these different shapes, and, hence, equal center cooling velocity, are as follows:

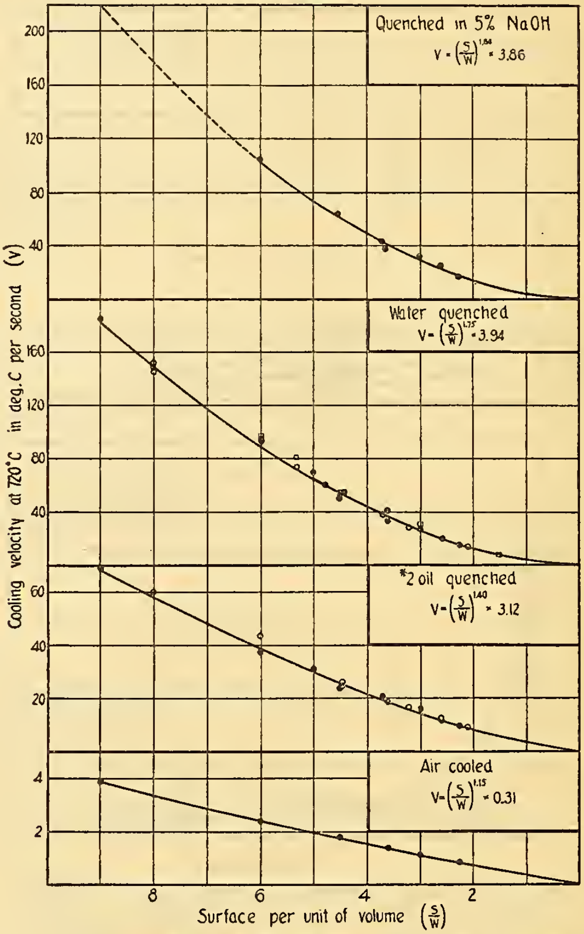


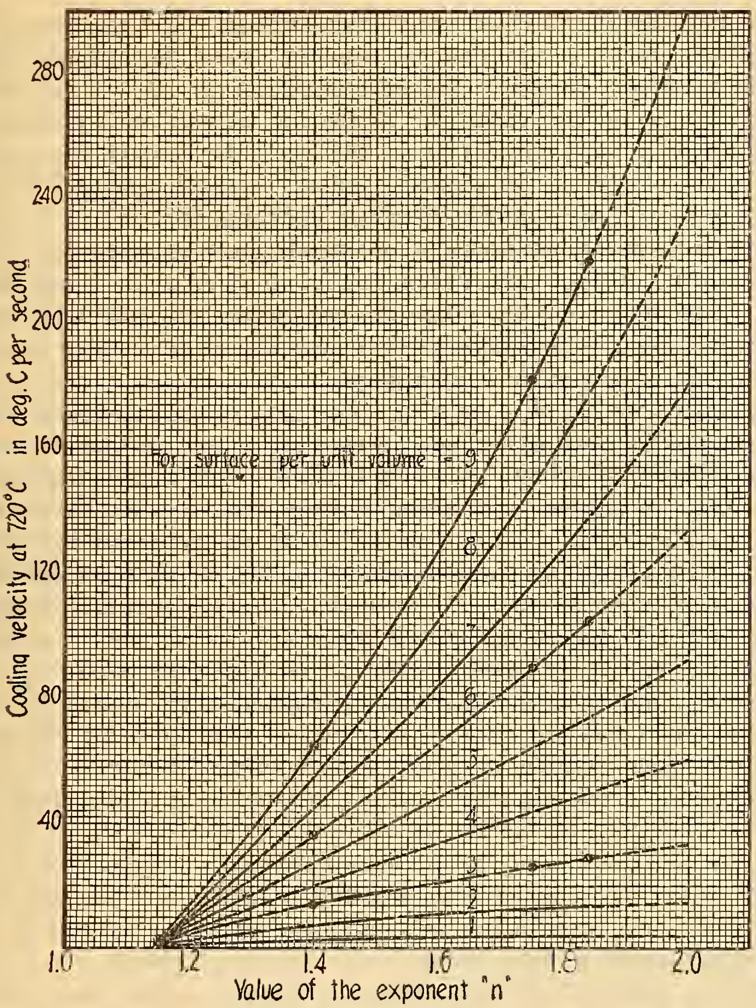
FIG. 7.—*Relation between the surface per unit of volume and the center cooling velocity, taken at 720° C. in various sizes and shapes quenched from 875° C. into different coolants*

Hollow circles represent determinations with spheres; solid circles with rounds; hollow squares with plates

Size in inches for—		
Length-diameter ratio for rounds	4:1	Infinite
Length-width-thickness ratio for plates	4:4:1	Infinite
Spheres	4	3
Rounds	3	2
Plates	2	1

The difference between these ratios for the finite and the infinite specimens is due to the greater cooling effect exerted by the end and edge surfaces of the short pieces.

To apply the foregoing to any coolant it is only necessary to know, for different values of surface per unit of volume, the relation between



F

FIG. 8.—*Mass effect chart*

This gives the relation between the center cooling velocity, taken at 720° C., the "n" of equation (7), and the surface per unit of volume for high-carbon steels quenched from 875° C. into any coolant

"n" and the cooling velocity. This is shown graphically by the family of curves in Figure 8 and can conveniently be used for any of the simple shapes. For example, if the prescribed cooling velocity is known when quenching a cylinder 1 inch in diameter and 6 inches long in a special oil, the numerical value of "n" for this coolant is

given by the intersection of the horizontal line at this cooling rate and the curve representing the surface per unit of volume of a 1-inch round by 6-inch long cylinder. Let it be assumed that the cooling velocity is known to be 25° C. per second. Since the surface per unit of volume of the designated cylinder is 4.33, the value of "n" equals 1.43.

By substitution in equation (7) the constant "C_2" can readily be obtained, and it is then possible to make use of the formula in the usual manner. However, the determination of "C_2" is not necessary. Knowing the value of "n" for the coolant, it is possible to scale directly from the curves in Figure 8, the cooling velocity for any value of surface per unit of volume. These lie along a vertical line projected from 1.43 which equals the value of "n."

Figure 8 gives the most useful of the relationships so far developed, for with it a close approximation can be obtained of the mass effects in quenching for a wide range of conditions. No calculations are required, and it is only necessary to know the center cooling velocity for one size in any of the simple shapes.

It will be well at this point to refer again to the conditions under which the described experiments were carried out, so that there will be no misunderstanding concerning the limits within which the various data may be applied. In the first place, the relations have so far only been shown to apply to the effects at the center of the simple basic shapes. For a complete understanding of the mass effects in quenching, a study must also be made of the temperature distribution, and it is expected that this phase will be covered in a subsequent report. In all cases a quenching temperature of 875° C. was employed, and both the steel and the coolant were kept motionless. As the customary methods of commercial treatment for relatively small sections involve agitation or circulation of liquids, such as water and oils, and likewise a variety of quenching temperatures are employed depending largely upon the composition of the steel, but also on the purpose of the treatment, practical application of the developed data requires consideration of these two variables: (1) The effect of motion in coolants on the cooling velocity and (2) the effect of quenching temperature on this cooling velocity.

Just as water and oil are different coolants so may each rate of motion or degree of circulation be properly considered as distinct from the motionless coolant. On the assumption that the rate of motion changes the speed of cooling there are, therefore, an infinite variety of coolants which must be considered, including not only changes in the composition but also in degree of motion and temperature. It is only necessary, as already stated, to have available the described cooling velocity for a known size and shape of high-carbon steel quenched from 875° C. into a given coolant in order to deter-

mine from Figure 8 the constant "n" and all data which can be developed for the motionless media used in the experiments. The accuracy of the results will, of course, be dependent upon the reliability of the cooling rate used as a basis for comparisons or calculations. The described data may now be summarized:

(*f*) In quenching simple shapes of various sizes (spheres, rounds, plates) the center cooling velocity is porportional to some power of the surface per unit of volume greater than 1 and less than 2. This power increases with the rapidity of the coolant used.

(*g*) When quenching from a definite temperature into a given coolant the center cooling velocity is determined by the exposed surface per unit of volume. Hence, it will be equal in spheres, rounds, and plates which have equal surface per unit of volume. This condition is fulfilled when the ratio of diameters of spheres and rounds of infinite length to the thickness of plates having infinite width and length is 3:2:1. When the length of the round is four times its diameter and the width and length are each four times the thickness of the plate, these ratios become 4:3:2.

6. EFFECT OF QUENCHING TEMPERATURE ON THE CENTER COOLING VELOCITY, TAKEN AT 720° C.

The effect of quenching temperature on the designated cooling velocity obtained in water and two oils is shown graphically in Figure 9, and it will be noted that in all cases the increase in rate is much more marked for a given temperature rise between 720 and 800° C. than above. From these curves conversion factors can be determined by which it is possible to change the cooling rates from the "standard" quenching temperature of the experiments, 875° C., into the rates which would be obtained from any initial temperature between 720 and 1,050° C., a range covering commercial hardening except for high-speed steels. As a matter of convenience the conversion factors are shown graphically in the right half of the diagram.

In addition to the direct experimental observations giving the changes in rates with quenching temperature, derived values for the conversion factors have been included in the curve at the right side of Figure 9. These were computed from data given in Figure 2 and depend upon two facts—(1) that the cooling velocity-temperature changes (neglecting thermal transformations) are of the same form when quenching the various sizes and shapes from different temperatures in a given coolant, and (2) for a given final temperature the maximum velocity throughout the cooling ranges is directly proportional to the initial (quenching) temperature, both with respect to its position in the temperature scale and its numerical value.

The many quenching curves taken to demonstrate these features can not be included in this report, nor will there be given in detail the derivation of the conversion factors by this method. It is to be noted, however, that the derived values show close agreement with those determined directly by experiment, and thus indicate that exceptionally consistent results have been obtained in the several sets of experiments.

The actual change in cooling velocity is larger in the rapid coolant than in those which cool the steel more slowly, but the conversion factors for the two oils and water are practically identical—at least, they are so close as to be within the limits of experimental accuracy.

From the data given in Figure 9 "the quenching temperature conversion chart" of Figure 10 has been prepared.

This gives for samples of different surfaces per unit of volume the conversion factors to be applied to the cooling velocity from one quenching temperature in order to determine the cooling velocity

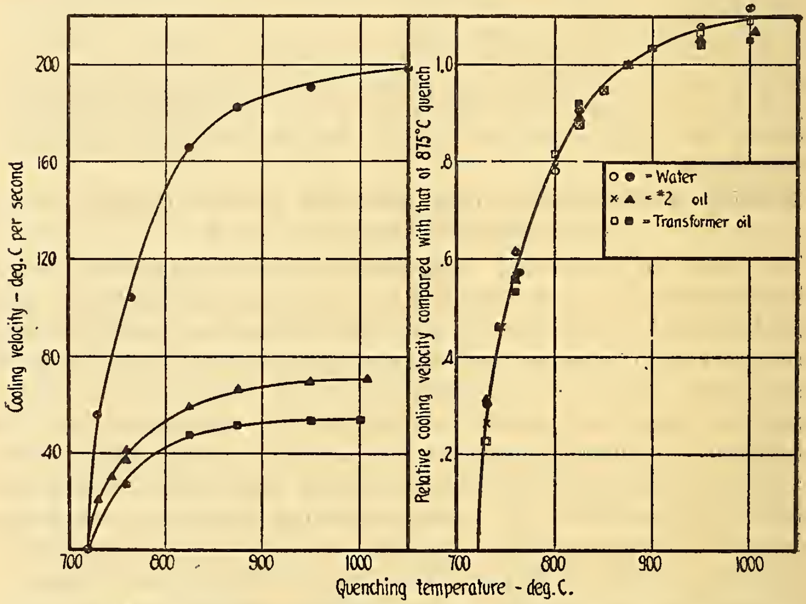


Fig. 9.—*Effect of quenching temperature on the center cooling velocity, taken at 720° C. in quenching high-carbon steel into either motionless water or oils at 20° C.*

Direct experimental results given as solid circles, triangles, and squares. Derived values, as explained in the text, are shown by crosses and hollow circles and squares

of the same sample when quenched in the same coolant from any other temperature between 720 and 1,050° C.

It applies generally to any coolant which gives cooling characteristics similar to those shown in Figure 2. Practically all of the oils and aqueous solutions so far tested at ordinary temperatures fulfill these conditions within the limits of accuracy attained in the described experiments. Included in this list are sodium hydroxide solutions, sodium, and also calcium chloride brines, dilute sulphuric acid, sperm, neat's-foot, transformer, cottonseed, machine, castor, olive, fish, and three commercial quenching oils. It does not, however, apply to air cooling.

In connection with Figure 10 the "mass effect chart" (fig. 8) becomes of very general use, as it is only necessary to reduce the

known value of the cooling velocity from one quenching temperature into the rate produced from 875° C. when the mass effects can be determined and a reconversion for quenching temperature made for the new size and shape. To illustrate the use of the "quenching temperature-conversion" chart, a number of examples may be cited.

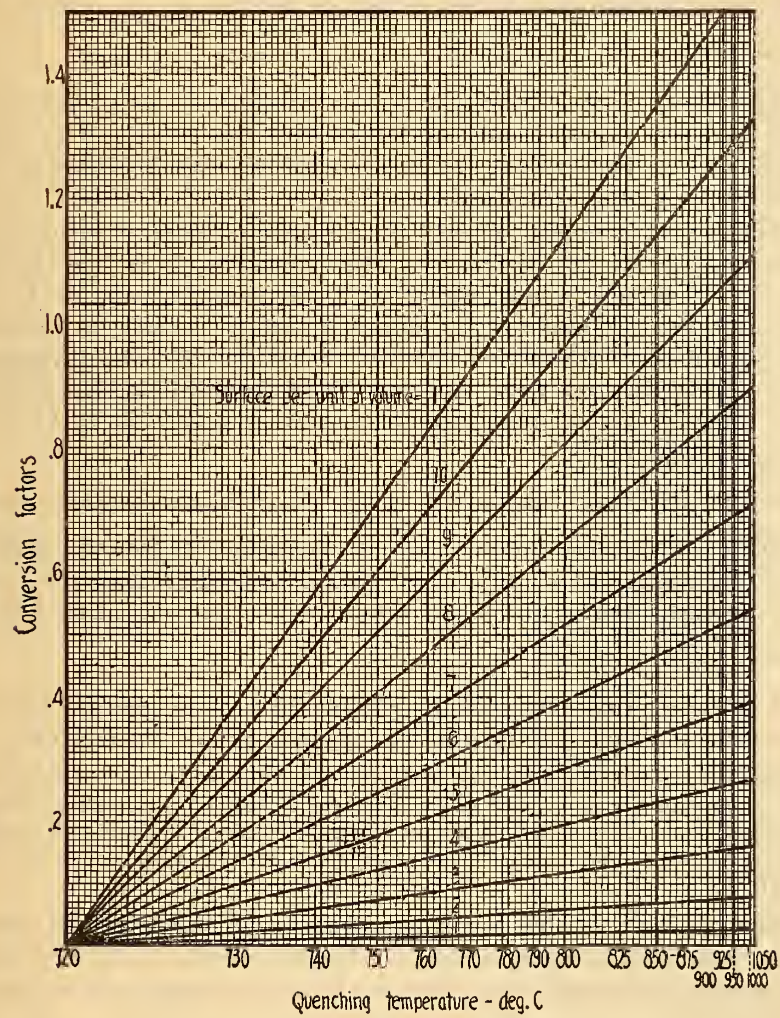


FIG. 10.—*Quenching temperature conversion chart*

This gives the relation between the quenching temperature and center cooling velocity taken at 720° C., for various sizes and shapes of steel with the oils and aqueous solutions having cooling characteristics similar to those shown in Figure 2

If the rate for a ½-inch round, 2 inches long (surface per unit volume = 9) is known to be 67° C. per second when quenched in a given coolant from 900° C. and it is desired to determine the rate when quenching from 760° C. under otherwise comparable conditions, the following procedure is employed:

First obtain in Figure 10 the intersection between the $\left(\frac{S}{W}\right)$ curve=9 with the quenching temperature of 900° C. The factor opposite this intersection is 1.03. Next follow the $\frac{S}{W}$ curve=9 in the direction of and until it intersects the new quenching temperature of 760° C. The factor opposite this intersection is 0.59. The cooling velocity when quenching from 760 will then be $\frac{0.59}{1.03}$ of that when quenching from 900° C. or $\frac{0.59}{1.03}\times 67=38°$ C. per second.

The described procedure is shown by the dotted lines in the chart.

A more complicated case in which both the "mass effect" and "temperature conversion" charts are used will now be followed and checked by actual experiments.

The selected cooling velocity for a ¾-inch round, 3 inches long (surface per unit of volume = 6), when quenched from 790° C. into 5 per cent sodium chloride was found by experiment to be 76° C. per second. It is desired to determine the cooling velocity in a ½-inch round, 2 inches long (surface per unit of volume = 9), when quenched from 875° C. into the same coolant. The following procedure is used:

1. First make the temperature conversion from 790 to 875° C. from Figure 10.

Find the intersection between the curve $\frac{S}{W}=6$ and the quenching temperature of 790° C. The factor opposite is 0.37. Next follow on this $\frac{S}{W}$ curve to the right until it intersects 875° C. The factor opposite this intersection is 0.49. The cooling velocity when quenching the ¾-inch round 3 inches long from 875 will then be $\frac{0.49}{0.37}\times 76=101°$ C/sec.

2. Convert this new cooling rate of 101° C. per second for the ¾-inch round into the rate for the ½-inch round from Figure 8.

Find the intersection of the line representing the surface per unit of volume of the ¾-inch sample (=6) with the cooling rate of 101° C. per second. Follow vertically from this point to the new surface per unit of volume (=9 for the ½-inch round). The intersection is found to be opposite to a cooling velocity of 211° C. per second.

The cooling rate obtained experimentally for the described conditions was found to be equal to 215° C. per second, which checks the value derived from the two charts (211° C. per second), within about 2 per cent.

Other comparisons between values derived from the two charts and experiment are given in Table 4 and show that consistent agreement is secured.

7. GENERAL LIMITS WITHIN WHICH THE DERIVED RELATIONS BETWEEN THE COOLING VELOCITY AND SURFACE PER UNIT OF VOLUME APPLY

There still remains for discussion the limits within which the derived relations between the cooling velocity and surface per unit of volume apply. Definite limits can not be set at this time, but the results of a few special experiments will serve to illustrate some of the principles involved.

A 1-inch diameter cylinder, 3½ inches long, with spherical ends was quenched in water from 875° C. and the center cooling velocity found to be 55° C. per second. This cylinder has a surface per unit of volume equal to 4.42 and according to formula (7) the cooling velocity would be 53° C. per second. Its surface per unit of volume is slightly less than the same cylinder without the spherical ends (4.56) for which a cooling velocity of 56° C. per second should be obtained.

TABLE 4.—*Comparison of direct experimental determination for cooling velocity taken at 720° C. with values derived from "mass effect" and "quenching temperature conversion" charts (figs. 8 and 10)*

Sample	Surface per unit volume	Coolant	Quenching temperature	Cooling velocity at 720° C., by experiment	Cooling velocity at 720° C. when quenching from 875° C.: Converted to $\frac{S}{W}=9$ by means of Tables 8 and 10	Cooling velocity at 720° C. when quenching from 875° C.: Direct experimental determination for $\frac{S}{W}=9$	Variation of (6) from (7)
1	2	3	4	5	6	7	8
			° C.				Per cent
¾ by 3 inch round	6	5 per cent NaCl	790	76	211	215	2
Do	6	H_2O	800	69	174	182	4.5
Do	6	Transformer oil	790	19	54	51	5.5
2+¾-inch sphere	2.1	H_2O	760	8.3	186	182	2
Do	2.1	No. 2 oil	760	4.6	65	66	1.5

A ⅞-inch square bar 3 inches long when similarly quenched in water from 875° C. had an experimentally determined cooling rate equal to 60° C. per second. Its surface per unit of volume equals 4.80 and according to formula (7) or the chart reproduced in Figure 8 its velocity should be 61.

In both these cases the modifications made in the basic shapes (spheres, rounds, and plates) did not involve very large changes in the surface per unit of volume, and the values obtained from the formulas and charts check the experimental data within the limits of accuracy attained. Therefore, a ¾-inch diameter cylinder, 3 inches long, was prepared in which the entire curved surface was threaded with ¾-inch United States standard threads, 10 to the linear inch. The surfaces per unit of volume of this threaded specimen and an unthreaded cylinder of the same length and diameter are respectively 11.0 and 6.0. The calculated cooling velocity for the threaded piece is 262° C. per second, whereas the actual rate obtained in quenching it was only 92° C. per second, which is practically identical with the calculated and actual cooling velocity of the plain cylinder, namely, 90° C. per second.

No very general conclusions can be drawn from such limited experiments, but they indicate that the described relations between cooling velocity and the surface per unit of volume do not apply when modifications in the simple basic shapes involve a large change in the surface without appreciably affecting the volume (or weight). With slight changes in form from the basic shapes which do not alter materially the ratios of surface to volume the formulas and charts will give results which approximate the actual values within about 5 per cent.

Obviously, they can not be considered for irregularly shaped masses which have no geometrical center at which to determine the cooling velocity, but in at least some of such cases it is reasonable to expect that the cooling velocity at the center of equal temperature planes would bear some definite relation to the surface-volume relationship. This might profitably be investigated, but would require a study of temperature distribution during cooling.

Another and more important question, as it relates to the simple shapes covered by the experiments, is whether the data can be applied to very large masses.

It has already been demonstrated that the relation between the center cooling velocity and the surface per unit of volume is represented by a family of hyperbolic curves having the general formula $V=\left(\frac{S}{W}\right)^n c_2$. As the value of the exponent ^{n} was found to vary for the different coolants, the curves will cross if carried far enough to include very large sizes.

In other words, oil would cool faster than water, and with sufficiently large masses even air would cool the center more rapidly than sodium hydroxide, etc. Obviously, such effects are unreasonable, and it may be stated at the outset that the several equations given in this report do not hold good in such cases. However, it is quite

reasonable for the center cooling velocity given by various coolants to be more nearly the same for large sections than in the relatively small samples used in the described experiments. A point must be reached with increasing mass where the effective surface through which the heat must be taken is so small in relation to the weight (or volume) and so far removed from the center that the cooling is a function of the thermal properties of the metal. No matter how quickly the surface is brought to the final temperature of cooling there must be a limiting rate by which heat can be withdrawn from the center, and this is controlled by the thermal properties of the material being quenched.

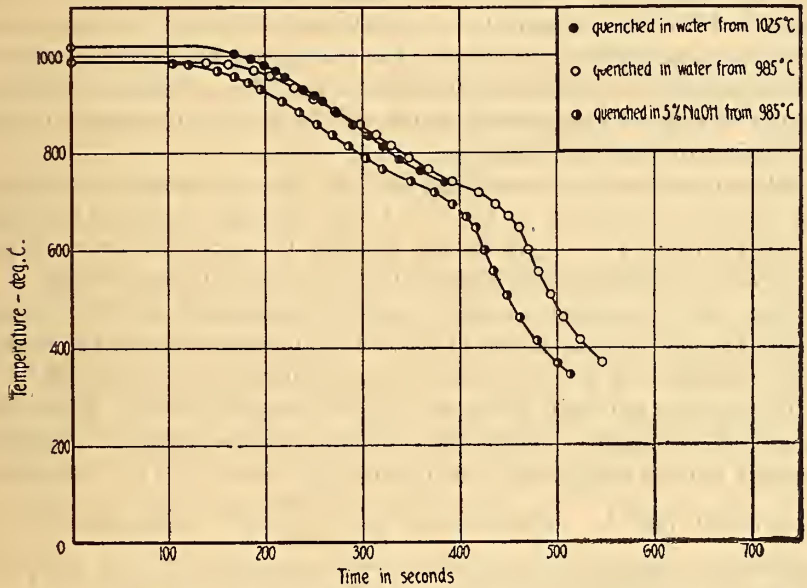


FIG. 11.—*Time-temperature cooling curves obtained at the center of a 11¼-inch diameter sphere quenched in various coolants from different temperatures*

This sphere was made from 0.19 per cent C steel

(a) RESULTS OBTAINED IN QUENCHING A SPHERE 11¼ INCHES IN DIAMETER

To determine whether equal cooling velocities are obtained under such conditions, in which the formulas show a supposed reversal of "hardening power" for various coolants, and likewise to compare the numerical values of cooling rates determined experimentally on large sections with those derived from the small size specimens, three quenching experiments were carried out with a sphere 11.25 inches in diameter. This was quenched from 985 and 1,025° C. into motionless water at 22° C. and also from 985° C. into motionless 5 per cent sodium hydroxide at 22° C. A 14-gauge chromel-alumel thermocouple and a portable potentiometer were used in taking the time-temperature cooling curves reproduced in Figure 11. Aside from the inconven-

ience in using the string galvanometer for low rates of cooling this change in equipment and methods was desired to check the accuracy of the determinations on the small samples. Special precautions were taken to maintain good contact between the thermocouple and the center of the sphere during both heating and cooling. The thermocouple was mounted on a threaded plug in such a manner that when screwed tightly into the hole bored to the center of the sphere it pressed the hot junction up against the metal.

Mention has already been made of the fact that the maximum cooling velocity throughout the cooling range is directly proportional, both with respect to its position in the temperature scale and its numerical value to the initial (quenching) temperature (provided the coolant and its temperature are fixed). In both water and 5 per cent sodium hydroxide the maximum velocity is found at about 0.8 of the quenching temperature. This, therefore, offers a simple method of comparison which will be used in discussion of the quenching of the large sphere.

When quenched in water from 985° C., the maximum center cooling velocity was found to be 1.4° C. per second (at 790° C.); from 1,025° C. it was 1.5° C. per second (at 820° C.); quenched in the 5 per cent sodium hydroxide from 985° C., it was 1.4° C. per second.

Thus, the maximum cooling velocity determined directly by experiment at the center of the 11.25-inch diameter sphere was the same when quenched in water as in the 5 per cent sodium hydroxide.

The surface per unit of volume of this sphere is 0.533. From the "mass effect chart" (fig. 8) or equation (7) the maximum cooling velocity can be computed as in quenching from 875° C., it occurs at from 700 to 720° C. These values times $\frac{985}{875}$ will then give the respective maximum rates when quenching from 985° C. A comparison follows of the derived values with the experimental data.

	Maximum cooling velocity, °C. per second	
	Derived value	Experimental value
Quenched from 985° C.:		
Into 5 per cent NaOH	1.35	1.4
Into water	1.40	1.4
Quenched from 1,025° C.:		
Into water	1.52	1.5

An exceedingly close check has been obtained. However, the important feature is that water and 5 per cent sodium hydroxide do not, as in the case of the small samples, give appreciably different center cooling velocities.

It is not, of course, possible from these few experiments to set definite limits within which the "mass effect chart" (fig. 8) or the hyperbolic curves between center cooling velocity and surface per unit of volume hold good. However, it appears that these curves are valid, within the prescribed limit of accuracy of 5 per cent, at all points until they cross the curve for water which is represented by the formula

$$V=\left(\frac{S}{W}\right)^{1.75}\times 3.94;$$

subsequently as the size increases the velocities in other media appear to approximate those given by water which has been shown to apply for very large masses.

It should now be evident why the exponent ^{n} of the several formulas can not, as previously mentioned in Section IV, 2, be used as a direct measure of the "hardening power" of coolants, for in large sections, as clearly shown by the experiments just described, little difference is observed in the center cooling velocity for widely different coolants. In such cases this is a function of the thermal properties of the metal.

(b) EFFECT OF VARIATION IN COMPOSITION OF METAL QUENCHED ON THE OBSERVED CENTER COOLING VELOCITY, TAKEN AT 720° C.

The described relations and charts have been based on experiments with high-carbon steels and can not be applied directly to metals having widely different thermal properties. A few quenching experiments were carried out to throw light upon the changes in cooling velocity which may be expected when such high-carbon steels are replaced by other metals and the results are given in Table 5.

TABLE 5.—*Cooling velocity obtained at 720° C. when quenching 3/4-inch diameter by 3-inch cylinders of various metals from 875° C. into motionless water at 20° C.*

Metal	Cooling velocity at 720° C. in ° C. per second
0.89 per cent C steel	93
"Armco" iron (about 0.025 per cent C)	[1] 97
32 per cent nickel steel	107
High-speed steel, 13 per cent W; 3.7 per cent Cr; 1.9 per cent V; 0.7 per cent C	92
Bar copper	146

[1] Derived value from experiment with ½-inch diameter by 2-inch long cylinder.

The differences in cooling velocity between the high carbon, high carbon-chromium, and high-speed steels and Armco iron are well within the accuracy of the experiments (5 per cent), but more rapid cooling is obtained in the 32 per cent nickel steel and copper. The described relationships may, therefore, safely be used for carbon

steels of varying carbon content (except when thermal transformations alter the cooling rates at 720° C.), ball race, and high-speed steels. Probably they also apply to the low alloy content structural steels. However, attention should be called to the fact that there are much larger differences in the cooling curves in the low temperature ranges. The selected cooling rate at 720° C. is taken while the steel is in the austenitic condition and the carbon in solution; it is therefore not related to the variations in thermal conductivity known to exist between steels of varying carbon content at lower temperatures where alpha iron exists.

V. SUMMARY AND CONCLUSIONS

The results obtained may now be summarized and the following conclusions drawn:

1. Effect of Size and Shape on the Center Cooling Velocity, Taken at 720° C.—(*a*) In quenching steel spheres, rounds, and plates the cooling velocity for any one of these shapes is inversely proportional to some power of the diameter (or thickness) greater than 1 and less than 2. This power increases generally with the rapidity of the coolant; it is close to 1 for still air (1.15) and approaches 2 in motionless water (1.75) and 5 per cent sodium hydroxide (1.84) at 20° C.

(*b*) For a given size the highest cooling velocity is obtained in spheres, an intermediate rate in rounds, and the lowest in plates. More specifically, for equal cooling velocity the ratio of the diameter of spheres to the diameter of rounds and thickness of plates is as 4:3:2, provided the length of the cylinders is four times the diameter and the length and width are each four times the thickness of the plates. With infinitely long cylinders and plates having infinite length and width these ratios are 3:2:1 (directly as the sizes which have equal surface per unit of volume).

(*c*) The cooling time is inversely proportional to the selected cooling velocity, provided it is taken over an interval which does not begin or end at a temperature within the range of large heat effects of transformations.

(*d*) The relations between the size and shape of steel quenched and the cooling velocity or time are closely approximated by the following formulas in which V is the velocity in ° C. per second, T is the time in seconds, D is the stated dimension (diameter or thickness) in inches, S is the surface area in square inches, W is the volume in cubic inches, and C, C_1, C_2 and ^{n} are constants.

(1) Cooling velocity and diameter or thickness

$$VD^n = C$$

(5) Cooling time and diameter or thickness

$$\frac{T}{D^n}=C_1$$

(6) Cooling time and velocity

$$T=\frac{CC_1}{V}$$

(7) Cooling velocity and surface per unit of volume

$$V=\left(\frac{S}{W}\right)^n\times C_2$$

Values of the several constants were determined for a variety of conditions, but the most useful relation is given by equation (7). From it and the described experiments a "mass-effect" chart was prepared by which it is possible to determine the center cooling velocity, taken at 720° C., of any size of the simple shapes quenched from 875° C., into any coolant, provided this velocity is known for any other size of one of these shapes when quenched from the same temperature into the same coolant. Conversions may be made directly from the chart.

(*e*) The cooling velocity obtained when quenching any of the simple shapes in a given coolant from a definitie temperature is a function of the exposed surface per unit of volume. When any two sizes of the simple shapes have equal surfaces per unit of volume, their respective center cooling velocities are equal.

2. Effect of Quenching Temperature on the Center Cooling Velocity, Taken at 720° C.—(*a*) Increase in initial temperature when quenching into ordinary oils and water at atmospheric temperatures increases the center cooling velocity. The magnitude of the change is greater for equal temperature rise between 720 and 800° C. than above; likewise it is greater in the rapid than in slow coolants, but the proportional change is, within the limits of experimental accuracy, the same for the oils as in water.

(*b*) A "quenching temperature-conversion chart" was prepared by which the cooling velocity given by one quenching temperature can be converted into that which would be obtained from any other temperature between 720 and 1,050° C.

3. General.—(*a*) The described relations apply to the simple shapes (spheres, rounds, and plates when made of various carbon and some alloy steels) and will give values within about 5 per cent of those determined experimentally. They likewise hold for modifications which do not materially alter the surface per unit of volume of the basic shape which has been modified, but do not apply in these cases in which there is no geometrical center.

(*b*) Since the center cooling velocity in quenching spheres, rounds, and plates is proportional to some power of the surface per unit of volume, depending upon the coolant used, these relations are represented by a family of hyperbolic curves which, if projected to large enough sizes, will cross. Actually the velocity can not exceed a certain value which appears to approximate that given by water irrespective of the coolant used. In such cases the rate at which heat is extracted from the center is a function of the thermal properties of the metal and is not affected by differences at the surface, which is small in comparison with the weight or volume and far removed from the center of the mass. The hyperbolic "mass-effect" curves for various coolants, therefore, appear to apply at all points until they cross the curve for water.

(*c*) Within the prescribed limits the "mass effect" and "temperature conversion charts" prepared will give the center cooling velocity (taken at 720° C.) when any size of the simple shapes is quenched from any temperature between 720 and 1,050° C. into the customary oils and aqueous solutions at atmospheric temperatures, provided only this velocity is known when quenching one size and shape from some temperature into the same coolant. The cooling velocity at 720° C. was chosen as a basis of comparison, as it had previously been shown to be the best single factor which can be taken from cooling curves to represent the hardening produced in carbon steels.

Acknowledgment is made to T. E. Hamill, laboratory assistant, for his assistance in carrying out practically all of the described experiments.

WASHINGTON, June 15, 1925.